Resolving the amalgam: connecting pedagogical content knowledge, content knowledge and pedagogical knowledge

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Resolving the amalgam: Connecting PCK, CK and PK

Abstract

This paper concludes the Special Issue (SI) "Probing the Amalgam: the relationship between science teachers' content, pedagogical and pedagogical content knowledge". We review the five papers (Sorge et al; Gess-Newsome et al; Kind; Pitjeng-Mosabala and Rollnick; and Liepertz and Bronowski) by discussing evidence these present regarding the relationships between content knowledge (CK), pedagogical knowledge (PK) and pedagogical content knowledge (PCK); the development of CK, PK and PCK in novice and experienced secondary science teachers and how CK, PK and/or PCK impact students' learning. In conclusion, we draw these findings together in offering proposals for future research via reconsideration of Shulman's amalgam. This includes post-hoc examination of a PCK model known as "the Consensus Model" (Gess-Newsome, 2015; Neumann, Kind & Harms, 2018) and presentation of a novel PCK structure based on evidence from the SI studies.

Introduction

This Special Issue (SI) builds on previous collaborative work on PCK, in particular the previous IJSE SI on this topic (Vol 30 No 10 2008) and the first PCK "Summit" held in 2012 (Berry, Friedrichsen, & Loughran, 2015). The SI papers present international perspectives that extend scholarly understanding of CK, PK and PCK. This closing piece draws these together, indicating ongoing challenges and how Shulman's (1987) "amalgam" may be considered relevant to current researchers.

As teacher education researchers and teacher educators, we are drawn to PCK as a construct. PCK is useful for thinking about teachers' professional knowledge and practices, potentially contributing to understanding of how and why teachers help students learn science. Our research (e.g. Chan & Yung, 2015, 2018; Kind, 2009a, 2016; Kind & Kind, 2011) and reviews (Chan & Hume, 2019; Kind, 2009b) utilise and reflect on interpretations of PCK. This paper addresses issues noted in the introductory paper (Neumann, Kind & Harms, 2018) that relate to unrealised potential of PCK to contribute extensively to teacher education policy and practice. To achieve this, PCK research should indicate how, why and what professional knowledge teachers develop. This

would shift the field towards a position that enhances PCK's explanatory power and offer a clear statement about how PCK contributes to understanding students' learning of science (Abell, 2008). Previous research demonstrates persistent, high level value for PCK in terms of describing teacher knowledge and teaching practice (Abell, 2008) and contributing positively to students' learning outcomes (Coe, Aloisi, Higgins & Major, 2014). The first PCK Summit (Gess-Newsome & Carlson, 2013) attempted to achieve consensus about PCK as a construct. Nevertheless, further work about the composition and development of PCK is desirable to support its inclusion in teacher education policy and practice. Accordingly, we review the "Consensus model" (Gess-Newsome, 2015) and propose work arising from this. Finally, we hope this SI contributes to strengthening PCK's position in the field of science education.

The paper has four sections. First, we discuss variance in interpretations of CK, PK and PCK in the five SI papers. Next, as discussed in the introductory paper, we review how the five papers contribute to understanding the construct under these headings:

- relationships between content knowledge (CK), pedagogical knowledge (PK) and pedagogical content knowledge (PCK)
- the development of CK, PK and PCK in novice and experienced secondary science teachers
- how CK, PK and/or PCK impact students' learning

Finally, we attempt to draw these findings together in a concluding section that offers proposals for future research.

Interpretations of CK, PK and PCK

The five papers illustrate differing perspectives on these types of teacher knowledge. Nevertheless, all five provide empirical evidence for and/or imply that CK is connected to PCK. While unsurprising for a special issue on the topic, we believe stating this constant outcome explicitly is valuable. In their meta-review Coe, Aloisi, Higgins, and Major (2014) refer to "(pedagogical) content knowledge" (p 18), in which "pedagogical" is deliberately bracketed, implying connection between these two types of teacher knowledge, but also uncertainty about pedagogy allied to teachers' CK. Authors in this SI agree that successful student learning requires "pedagogical content knowledge" that relies on "content" knowledge quality.

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These SI papers present mixed opinions about CK. Three base their positions on Schwab (1964). Liepertz and Borowski (2017) and Sorge, Kröger, Petersen, and Neumann (2017) combine Schwab's (1964) substantive (in terms of concepts and facts) and syntactic knowledge (in terms of logical structures of a science), describing CK as a comprehensive knowledge base. This is consistent with German teacher education practice in which pre-service teachers are taught content separately from pedagogical knowledge. In Germany, teacher education tends towards a subject-oriented perspective. Kind (2017) takes Schwab's (1964) position that CK comprises facts about concepts and information only. She emphasises CK quality, noting, in line with Ball and McDiarmid (1990) that poor CK reduces chances for students' learning, so teachers must understand the concepts and topics they present. This is consistent with England's National Curriculum emphasis on science content (Department for Education, 2014). The two remaining papers, Pitjeng-Mosabala and Rollnick (2017) and Gess-Newsome et al. (2017) do not propose any internal CK structure. It is not immediately apparent if these positions are consistent with practices in South Africa and the US respectively. Gess-Newsome et al. (2017) create a new term, "academic content knowledge" (ACK) which equates to Kind's CK. They define this operationally as linked to PCK. Their rationale lies in the "body of work that can link more specific measures of content knowledge… in particular, the kinds of content knowledge that are relevant to teaching, to student gains" (p 18 – 19). Pitjeng-Mosabala and Rollnick (2018) regard CK as a "necessary precursor" (p 742) to PCK that underpins topic-specific professional knowledge (TSPK). Hence, the SI papers follow a trajectory from defining CK tightly as a comprehensive knowledge base to no formal definition. A reasonable position (implicit for Pitjeng-Mosabala and Rollnick and Gess-Newsome et al.) is that, as a minimum, CK comprises knowledge about concepts and facts to be taught.

Authors' definitions of pedagogical knowledge (PK) also exhibit variation. Liepertz and Borowski (2017) and Sorge et al. (2017) describe pedagogical knowledge (PK) as comprising classroom management, teaching methods, individual learning processes and assessment of (student) performance. Gess-Newsome et al. (2017) introduce a novel term, "GenPK", rather than PK. GenPK is defined as the ability to implement general teaching skills that potentially super-cede content. The precise nature of "general teaching skills" is unspecified. Implicitly, classroom management is included, which overlaps with Sorge et al and Liepertz and Borowski. Kind (2017) and Pitjeng-Mosabala and Rollnick (2018) refer to "topic-specific professional knowledge" (TSPK), not PK, adopting the Consensus Model (Neumann, Kind & Harms, 2018; Gess-Newsome, 2015; Figure 1).

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[INSERT FIGURE 1 ABOUT HERE]

Within the Model TSPK may vary. The first line of the Model suggests a teacher may develop TSPK by drawing on PK and any combination of knowledge of assessment, curriculum, content and students. The Model does not specify the precise nature of PK. Three PK variants are presented in these five papers. One (Sorge et al and Liepertz and Borowski) includes sub-components that equate to knowledge of assessment and knowledge of students. Both these are separate teacher knowledge bases in the top line of the Consensus Model. Sorge et al and Liepertz and Borowski include classroom management and instructional strategies in PK. In the Consensus Model, instructional strategies are formed from the teacher knowledge bases (top line), while classroom management is not shown at all. The second variant (Kind and Pitejeng-Mosabala and Rollnick), does not define PK, but regards this as an aspect of teachers' topic-specific professional knowledge. The third (Gess-Newsome et al) describes PK as "general teaching skills".

Achieving a precise definition for PK would be beneficial, as the contrasting-yet-overlapping positions adopted by Sorge et al/Liepertz & Borowski and Pitjeng-Mosabala & Rollnick/Kind are incompatible. Gess-Newsome et al's "general" is unsatisfactory, as this could include any teacher behaviour/action. Teacher education practices would be clarified by resolving the extent to which PK is a distinct knowledge base. Assuming so, understanding what PK comprises would be helpful. For example, Sonmark, Revai, Gottschalk, Degligiannidi and Burns (2017)'s quantitative pilot study validated an instrument to analyse PK, collected data from an international teacher sample in terms of "assessment, instructional processes and learning processes" (p 4). This assumption about PK's nature was based on Guerriero's (2017) theoretical study. Teacher learning opportunities provided to teachers (including pre-service teachers) lay with Teachers must create environments in which students can learn: without this, content knowledge has no impact on learning. Teachers must know and apply instructional strategies that capture students' attention and lead to learning. Thus, we propose that PK comprises classroom management; ensuring constructive and positive student behaviour (which utilises classroom management); instructional strategies; and organisation of resources and materials.

Table 1 summarises SI authors' interpretations of PCK. Variation is observed in several aspects: the extent to which PCK is personal (developed by one teacher) or canonical ("widely agreed upon and formed through research and/or collective wisdom of practice" (Smith & Banilower, 2015, p. 90)); whether or not PCK has internal constructs;

and if PCK can/should be labelled "topic-specific" or specific to a discipline (Veal & MaKinster, 1999). Each variation is discussed.

[INSERT TABLE 1 ABOUT HERE]

Kind (2017) recognises personal and canonical PCK. Personal PCK may be developed or adapted by a teacher for use in a specific context, based on his/her experience. Canonical PCK may be agreed and used by a group of teachers working in a school, exemplified in shared or common practices. Kind considers PCK as an amalgam of instructional strategies, content representations and content knowledge (CK), based on Shulman's original (1987) definition. Pitjeng-Mosabala and Rollnick (2018) argue for "differentiating PCK in knowledge and practice" (p 744), and note differences between "personal" and "canonical" PCK. Meanwhile, Liepertz and Borowski (2017) acknowledge personal PCK, proposing that teachers draw on PK, CK and PCK separately to create personal teacher knowledge. Their work utilised tests reported in an earlier paper by Kirschner, Borowski, Fischer, Gess-Newsome, and Aufschnaiter (2016). They define PCK as knowledge about experiments, concepts and students' preconceptions. Conversely, Sorge et al adopt the view that PCK is canonical rather than personal, and can refer to aspects general to the discipline, specific to a topic or to a concept.

In making recommendations about PCK based on these positions, we recognise that teachers acquire PCK from a variety of sources. These include: prior experiences as students; imitating a more experienced teacher; canonical practices acquired through discussion and instruction by colleagues; and idiosyncratic practices that a teacher creates alone. The variety means that a PCK definition must be sufficiently flexible to apply in the range of settings and contexts in and from which teachers work and learn.

The SI papers offer two routes towards clarifying and understanding PCK. The first is via connections between CK and PK (Gess-Newsome, et al. (2017). This leads to the possibility that PCK has internal constructs. Gess-Newsome et al.'s (2017) evidence suggests interconnectedness between knowledge types is indicative of the quality of instruction (p 13). Thus, this route proposes PCK is composite knowledge derived from teachers' other knowledge bases. Stronger connections lead to better quality PCK. In this route, PCK varies depending on students, context, environment and strength/depth of knowledge held by a teacher. A second route refers to PCK as "topic-specific professional knowledge" (Sorge et al 2017; Kind, 2017). The Consensus Model implies

this is pre-filtered/pre-amplified PCK, as the position of TSPK (Consensus Model line 2) precedes the "filter" of teacher beliefs and orientations (Consensus Model line 3). Pitjeng-Mosabala and Rollnick create further variation by applying the term "topic-specific PCK" (TSPCK). Their PCK is at "the most specific level", noting that teachers' PCK would "be expected to vary by topic". In this route, each topic taught by a teacher requires precise PCK distinct from that used to teach any other topic. Developing PCK requires teachers to draw on knowledge base components that include CK and PK, but exactly how these connect is not measured. This route suggests PCK comprises a series of discrete "teacher practices". Their quality can be estimated by impact on student learning. The origins and composition of the practices (how a teacher interconnects CK, PK and any other knowledge) is not considered.

CK and PK are present in the PCK definition offered in both routes, but in different ways. CK is represented as facts or overviews of a group of facts, while PK is found as classroom management and instructional strategies. PCK may draw on teachers' knowledge of assessment, curriculum and students (Consensus Model Line 1). However, the notion that PCK is "topic-specific" is tautological. PCK must be topic-specific to be classified as PCK. Hence, positioning TSPK as a precursor to PCK in the Consensus Model is unnecessary. The connections route is more productive in defining PCK consistently. Adopting this position reduced the tendency PCK prevalent in models in extant literature that raise or lower the status of multiple components according to authors' personal preferences (for example, Magnusson, Krajcik, and Borko (1999); Mavhunga and Rollnick (2013);Tepner et al. (2012)). In the closing section a structure is proposed that can act as a framework for future research that accommodates PCK evidenced in the SI papers.

Relationships between content knowledge (CK), pedagogical knowledge (PK) and pedagogical content knowledge (PCK)

The five papers investigated these relationships. Sorge et al. (2017) and Liepertz and Borowski (2017) investigated PK, CK and PCK held by pre-service teachers at different stages of their teacher education, showing correlations between content knowledge (CK), pedagogical knowledge (PK) and PCK. They conclude that PCK is an amalgam of content and pedagogy. At this point, these authors remove "knowledge" from sub-component names, suggesting that the combined outcome, PCK is a separate, new entity.

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Kind (2017) focuses on the quality of pre-service teachers' PCK, presenting a rubric that identifies salient aspects termed "relevance" and "correctness" of CK and topic-specific PK. Her study assumes these two knowledge bases combine in generating PCK, emphasising that "high quality" CK and PK are required to generate student learning. An implication is that, over time, the quality of a teacher's PCK may shift as s/he learns knowledge and practices that are effective in generating accurate student learning of science concepts.

Gess-Newsome et al. (2017) and Pitjeng-Mosabala and Rollnick (2018) evaluated outcomes of professional development interventions using pre- and post-tests for experienced and novice teachers. Gess-Newsome et al. (2017) focused on a long-term professional development programme for experienced teachers' PCK teaching multi-topics in biology; Pitjeng-Mosabala and Rollnick (2018) measured the impact of a short-term professional development intervention focused on supporting novices teaching a single topic in chemistry. Pitjeng-Mosabala and Rollnick (2018) report that CK and PK connected, as improvements in CK were consistent with those in TSPCK and vice versa. Similarly, Gess-Newsome et al. (2017) report evidence that teachers' selection of instructional practices utilises "at least two internal constructs" (p 9) of PCK, namely PCK-CK and PCK-PK.

Thus, evidence emerges that CK and PCK (regardless of labels and internal structures) interconnect in teachers' instructional practices with consequences for learning; these papers suggest that when teachers' CK is strong their PCK is more likely to help students learn than when CK is poor. CK and PCK begin to interconnect during pre-service (initial) teacher education, with subsequent changes occurring through classroom practice and professional development. The nature, intensity and strength of interconnections vary depending on the quality, length and type of training and support received, as well as teachers' reflections on practice and context. Interconnections occur irrespective of variations in definitions of knowledge types. The next section discusses development of these knowledge types in greater detail.

Development of CK, PK and PCK in novice and experienced secondary science teachers

The SI papers confirm that development of PK, CK and PCK in teachers of different levels of experience is prompted by teacher education and professional development. Three (Kind, 2017; Pitjeng-Mosabala & Rollnick, 2017; Sorge et al., 2017) discuss research undertaken with novice teachers. Two (Kind, 2017; Sorge et al., 2017) adopt

convenience samples of trainee teachers. Kind (2017)'s paper reports data collected at the start of a teacher education programme, so development is absent, yet implied. The remaining four papers show changes in teacher knowledge over time.

Sorge et al. (2017) studied German teacher education showing that correlations change as teachers develop: PK scores correlate with PCK scores in the beginning, while later on, PCK scores correlate with CK scores. This is consistent with evidence of development of PCK over time, in that teachers' initial concerns about general pedagogical practice subside in favour of delivering content. The authors note closer integration occurs between knowledge types over time. Similarly, Liepertz and Borowski (2017), in line with Cauert, Liepertz, Borowski and Fischer (2015) found that in their model CK, not PK, "showed a significant influence on PCK" (p 13). This reinforces the centrality of CK in developing high quality PCK.

Pitjeng-Mosabala and Rollnick (2017) focus on unqualified interns as a unique group of teachers. Unqualified interns contribute to educational systems in many nations, so assuring quality of the teaching they deliver is pertinent. This paper shows that intensive professional development may impact topic-specific PCK which transfers into the classroom. Kind's analysis of novice teachers' planned PCK shows this group are not "blank slates" in terms of their professional knowledge. Her work evidences "traditions" persisting from teachers' prior experiences as students. Nevertheless, some novice teachers in Kind (2017)'s study proposed individual pedagogies which can be regarded as "personal" PCK. Kind (2017)'s topic-specific PCK grading shows variation in quality, which implies different impact on students' learning may arise.

Gess-Newsome et al (2017)'s research, with experienced teachers, generated evidence that provides a nuanced view of the impact of an intervention on practice. PCK-CK correlated most strongly with ACK, yet "practice" showed significant correlation with General Pedagogical Knowledge ("GenPK"). Qualitative evidence showed experienced teachers' practices benefited from enhanced emphasis on student learning.

Stating the obvious, becoming a professional teacher involves combining subject matter ("content") knowledge with learned pedagogical strategies that acknowledge the relatively novice level of subject knowledge held by a student audience. Cauert, et al. (2015) noted this as "domain-specific" knowledge. Teachers hold subject matter knowledge from previous educational experiences (most frequently school and / university) and, possibly via work experience. Their PCK as Shulman (1986, 1987) stated,

is professional knowledge acquired that distinguishes a "teacher" from a "subject specialist". Accordingly, PCK emerges as expertise develops, gradually becoming central to teachers' practice. Teacher educators and school mentors (terminology varies) apply judgement that determines when novice teachers attain appropriate professional standards. Evidence in these papers suggest that initially, novice teachers' PK develops first, suggesting PCK relies initially on PK (Sorge et al., 2017). CK connections emerge as novice teachers' learn how to amalgamate CK with classroom management and instructional strategies. Hence, these papers contribute evidence that teachers with accurate CK tend to develop good quality PCK, which provides a platform for further development towards excellence and mastery. Thus, PCK of different qualities emerges throughout a teacher's trajectory: s/he may rely initially on canonical and planned PCK developed by colleagues, prior to establishing personal PCK consistent with individually generated instructional strategies.

How CK, PK and/or PCK impact students' learning

Two papers test how CK, PK and PCK impact students' learning. Counterintuitively and in conflict with existing findings (Alonzo, Kobarg, & Seidel, 2012; Sadler, Sonnert, Coyle, Cook-Smith, & Miller, 2013), Gess-Newsome et al. (2017) report lack of correlation between teachers' PCK, practice and student achievement. They note this contradicts their qualitative data, which indicate strongly positive connections between teachers' perceptions of changes to their practice and students' learning. Liepertz and Borowski (2017) state their assumption that teachers with higher CK and PK (as teacher professional knowledge bases) and PCK apply their knowledge better in classrooms, so provide meaningful learning environments to successfully initiate student learning. However, unexpectedly their data suggest that teachers' PCK is negatively related to student achievement. These outcomes may arise due to several factors. First, methods used to measure the constructs may be measuring something other than professional knowledge applied by teachers when delivering content to students. This "something" could be CK or PK. If so, this casts doubt on whether PCK can be defined precisely. More optimistically, the tests may probe PCK that participants didn't (yet) possess or use. For example, Gess-Newsome et al. (2017) report that as their intervention progressed, teachers reverted to pre-intervention practices, although their data collection test focused on post-reform practices. Post-reform, a decline in teachers' performance on the PCK test would be expected, as this probed practices trained in the intervention. Liepertz and Borowski (2017) state their PCK test covered "widely accepted" aspects of the construct, but were normatively set. This creates potential for varied outcomes in novice teachers, as PCK develops differently in each individual. Additionally, Gess-

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Newsome et al. (2017) suggest time is required for new practices to embed. A two year intervention may therefore have limited impact on students' learning. Also, dilution of impact may occur, as the intervention must be assimilated first into teachers' knowledge, then their practice and ultimately student achievement. From a teacher's perspective, personal PCK may prohibit change, as once this is developed and found to be effective further alteration becomes hard to justify. Further, canonical PCK may dominate, for example, via detailed documents prepared by teachers in schools describing instructional strategies. Canonical PCK supports consistent delivery of curricula to student cohorts. Documentation supplies details about teaching concepts using resources and materials available in the specific school context. An unintended consequence is prohibiting or limiting impact of a potentially valuable intervention. Changes must be agreed by collaboration involve alteration of well-established practices as well as new resources. Finally, PK may constrain instructional practices in contexts or settings where, for example, student behaviour and limitations of resources may take effect.

Thus, enhancing teachers' PCK with expectations of enhancement in students' learning remains one of the most challenging aspects in teacher education. An emergent perspective is evidence for PCK types, namely, personal, canonical and discipline-specific may be relevant to this. Sorge et al. (2017) suggest that, initially at least, novice teachers rely on PK, with CK becoming important in teachers' practices over time. Personal PCK develops as a teacher makes individualised refinements to practice. This is potentially productive in enhancing student achievement. Over-reliance on canonical PCK developed by experienced teachers may be challenging for novices to implement, prohibiting development of personal PCK. To test this, understanding PCK types and contextual, personal and collaborative factors that may impact development of these is required. Currently, policymakers, curriculum and assessment developers as well as teacher educators may be under-estimating the strength of individual and group collaborative practices in deciding how to teach.

Probing the amalgam: A structured proposal for future PCK research

Analysis of the SI articles leads to rethinking how the Consensus Model clarifies and addresses diverse views about PCK (Gess-Newsome, 2015). As discussed elsewhere (Chan & Hume, in press; Kind, 2009b), researchers claim that PCK comprises many different combinations of teacher knowledge components. Indeed, the Consensus Model is not specific about PCK's composition. This implies an "anything goes"

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Feyerabend-like principle (Chalmers, 1982). This is liberating for researchers who may claim the Consensus Model as a theoretical framework for investigations from many perspectives. However, lack of specificity contributes to instability surrounding PCK as a construct, contributing to constraints on PCK's contribution to teacher education. Hence, in this SI, editors decided to refocus on Shulman's original proposal that PCK is an amalgam of subject/content knowledge and pedagogical practices based on instructional strategies and knowledge of students. Evidence emerges from these papers (and others published elsewhere) that CK and topic-specific professional knowledge or PK are connected consistently when teachers are developing their PCK. In probing the "special amalgam" (Shulman, 1987, p 8), these papers support Shulman's proposal that PCK comprises subject matter (however described) and pedagogical practices (whether topic-specific or general). There is a strong case, therefore, for PCK research to proceed from this position.

A second challenge the Consensus Model does not address explicitly is PCK type (personal, canonical, discipline-specific) or its sources. This contrasts with evidence in the SI papers which suggests PCK exists in multiple forms, relative to teachers' levels of experience. Thus, the Model offers no understanding of teachers' developmental trajectories and /or how/ if contextual and collaborative factors impact these. However, the Consensus Model includes "amplifiers and filters" that recognise teachers' thinking about their practice either as individuals or collaboratively. This may lead to development of core "beliefs" about personal practice and generate impact of teachers' actions on students' learning. Amplifiers and filters may underpin PCK development and types of PCK. As professionals, teachers make independent judgements and enact insightful decision-making. "Great" teachers are fully aware of "what works" in their settings, applying pedagogical reasoning in specific contexts. This may be based on personal, canonical or other types of PCK that comprise content and pedagogy. Weak teachers proceed with poorly judged PCK, regardless of learning outcome, exhibiting limited pedagogical reasoning.

[INSERT FIGURE 2 ABOUT HERE]

Our proposal (Figure 2) offers a structure for the amalgam. The proposal utilises aspects of the Consensus Model and builds on evidence presented in the SI. A premise for the

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structure is that PCK is professional teacher knowledge comprising CK and general / topic-specific PK. Hence, these two types of knowledge are shown as components (brackets on the right-hand side). Figure 2 attempts to show three additional points about PCK. First, PCK develops over time. The structure uses a wedge-shape to illustrate our expectation that a teacher's PCK develops and deepens over time as s/he progresses from "novice" to "experienced". Teacher knowledge may reach a status quo position over time, becoming hard to change for a variety of reasons. Nevertheless, this is not the same as claiming that PCK is universally fixed in all teachers from the moment they begin their careers. This attempts to address critique levelled at Shulman's original proposal that PCK is "static" (Cochran, Deruiter & Kind, 1993; Banks, Leach & Moon, 2005). A static model of teacher education may mean ensuring teachers learn a prescriptive set of teaching techniques or "tips for teachers", developing fixed professional knowledge from these. Second, PK comprises sub-components. The structure shows instructional strategies, classroom management, organisation of materials and resources, knowledge of assessment and knowledge of curriculum. These sub-components draw on evidence presented in the SI papers. This also supports teacher development over time, as the range of components within a teacher's knowledge base deepens. Dotted lines in the structure represent an attempt to show that the types of knowledge interact. The widths assigned to each component suggest greater increases in knowledge of instructional strategies and classroom management than the other components. We are not claiming that every example of PCK must contain all these types of knowledge; only that, on the basis of available evidence including the SI papers, these sub-components seem to be present consistently. CK is limited to comprising facts and concepts. Third, knowledge of students is a consistent factor that impacts PCK. Indeed, Shulman (1987) listed "knowledge of learners and their characteristics" as a separate teacher knowledge base component. Knowledge of students is proposed as a "bridging" component between PK and CK. This aids teachers making appropriate judgements regarding selection of instructional strategies for conveying specific CK to a student group. Placing knowledge of students between PK and CK is consistent with evidence in the SI papers, which do not show this is a sub-component of either PK or CK. The structure refines the Consensus Model, which is not specific about PCK's composition. PK and CK were identified as PCK components from the SI studies (Table 1), a literature review and the work of eleven PCK researchers (Berry, Nilsson, van Driel, & Carlson, 2017; Chan, Rollnick, & Gess-Newsome, in press). Integration between CK, PK and additional knowledge base components highlights how

coherent interconnection informs teachers' practices (Park & Chen, 2012). However, the structure shows the width of the CK "wedge" changing relatively little compared to that for PK. This is based on novice teachers' professional knowledge comprising strong CK, but relatively weak PK. On starting to teach, PK is much more likely to develop than CK. The use of "knowledge of students" as a bridging component recognises the need for a mediating link between pedagogy and content. A potential refinement may be regarding knowledge of students as a form of pedagogical reasoning that is crucial if teachers' judgement and actions are to achieve instructional goals (Shulman, 1987).

The structure does not discuss personal and canonical PCK. These types were identified in the Consensus Model, the SI papers (Table 1) above and through scholarly debate (Chan & Hume, 2019). "Types" of PCK arise from consideration of: ownership, that is, canonical or personal and individual or collective; grain size, that is, concept-, topic- or discipline-specific; enactment, that is, static, planned, or enacted; and teaching cycle phases, for example, planning and reflection. Of these, ownership appears to be central to understanding teacher development. The reliance on personal and canonical PCK for a novice and experienced teacher is likely to vary. For example, a novice may have developed little personal PCK, and be heavily reliant on canonical PCK, written in school-based teaching documents. An experienced teacher may have internalised the same canonical PCK, adapted into a personalised teaching style amounting to personal PCK. Representing this in one structure requires further evidence to justify how best to do this. As indicated above, PCK is by definition topic-specific, so grain-size is not essential to an overall structure. Enacted PCK is directly connected to a teacher's judgement and action. These aid consideration of PCK's origins and possible impact of teacher education and professional development on teachers' practices. However, they are not central to understand the amalgam itself.

Conclusion

The SI has attempted to probe the amalgam that PCK comprises content and pedagogy, and is teachers' "special form of professional understanding" (Shulman, 1987, p 8). The papers presented confirm Shulman's (instinctive) position and contribute to PCK research arising from his original proposals. As indicated above, PCK comprises content and pedagogy. We offer a layered structure that places these components at the centre, comprising knowledge on which teachers draw in constructing PCK, components within PCK and PCK types. We are aware that as this Special Issue was being prepared, a Revised Consensus Model (RCM) for PCK has been proposed (Carlson & Daehler, 2019),

further extending scholarly debate on the construct. Nonetheless, providing teachers with support to create PCK from baseline knowledge and facilitating its deployment in a teacher's classroom to ensure quality instruction and positively impact student learning outcomes seems essential. How science teachers develop, the experiences that influence their development, why they teach as they do and why / how they change in response to innovations are areas that PCK research could usefully inform. Van Driel, Berry, and Meirink (2014) eloquently argue

> "high-quality PCK is not characterized by knowing as many strategies as possible to teach a certain topic plus all the misconceptions student may have about it but by knowing when to apply a certain strategy in recognition of students' actual learning needs and understanding why a certain teaching approach may be useful in one situation" (p.865).

We agree with their view that the most successful teachers have flexible PCK that adapts quickly in classroom settings as they see students' varied responses to planned instruction. Such teachers will access instructional strategies which may be topic-specific or general pedagogical. Acquiring PCK of sufficient depth and quality to impact student learning positively lies at the heart of teacher education and professional development.

We also concur with Abell (2008), noting that science teaching is not acquisition of a "bag of tricks" that transfers easily from master to apprentice as a set of agreed, general pedagogical practices; and that PCK continues to have value in providing insights about learning to teach science, which should affect how students learn science. The next step is to meet the challenge of ensuring positive impact on students learning science.

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Authors	PCK Composition	PCK type(s) investigated
Gess-Newsome et al. (2017)	• Content knowledge (PCK-CK) • Pedagogical knowledge (PCK-PK) • Contextual knowledge (PCK-CxK)	• Topic-specific • Personal and Canonical • Enacted (planning, enactment and reflection)
Kind (2017)	• Content knowledge • Topic-specific professional knowledge	• Topic-specific • Canonical • Enacted (planning)
Liepertz and Borowski (2017)	• Topic-specific professional knowledge comprising Knowledge about experiments Knowledge about concepts Knowledge about students' preconceptions	• Topic-specific • Canonical • Static
Pitjeng-Mosabala and Rollnick (2018)	• Topic-specific professional knowledge comprising Learner prior knowledge Curricular saliency What makes a topic easy or difficult Representations Conceptual teaching strategies	• Topic-specific • Collective • Personal • Canonical • Static • Enacted (planning, enactment and reflection)
Sorge et al. (2017)	• Topic-specific professional knowledge comprising Knowledge of student cognition Knowledge of instructional strategies Knowledge of curriculum Knowledge of Assessment	• Topic-specific • Canonical • Static

Table 1: Interpretations of PCK in the Special Issue papers

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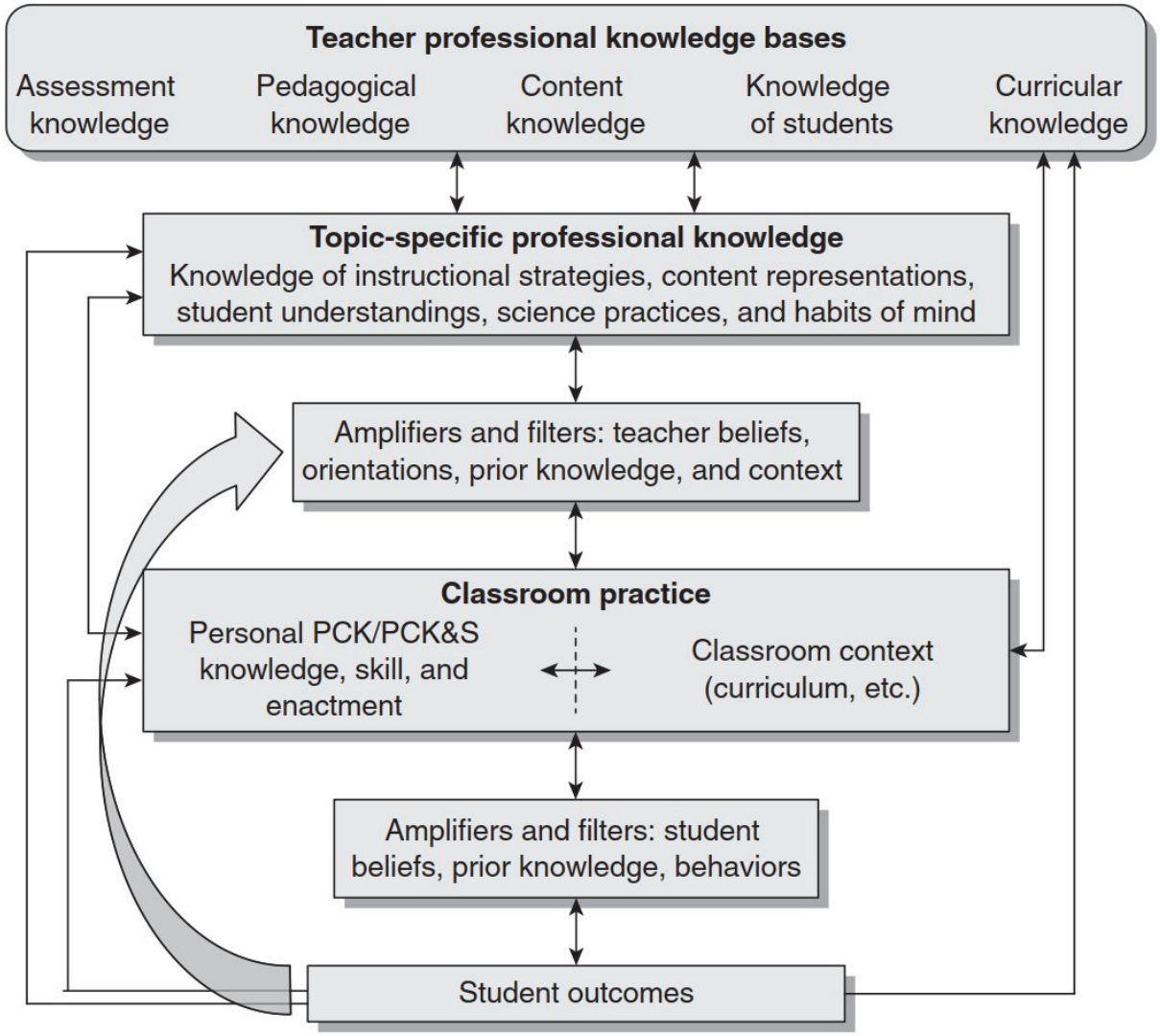

Figure 1: The Consensus Model of teacher professional knowledge and skill including PCK and influences on classroom practice and student outcomes (Gess-Newsome, 2015, p 31).

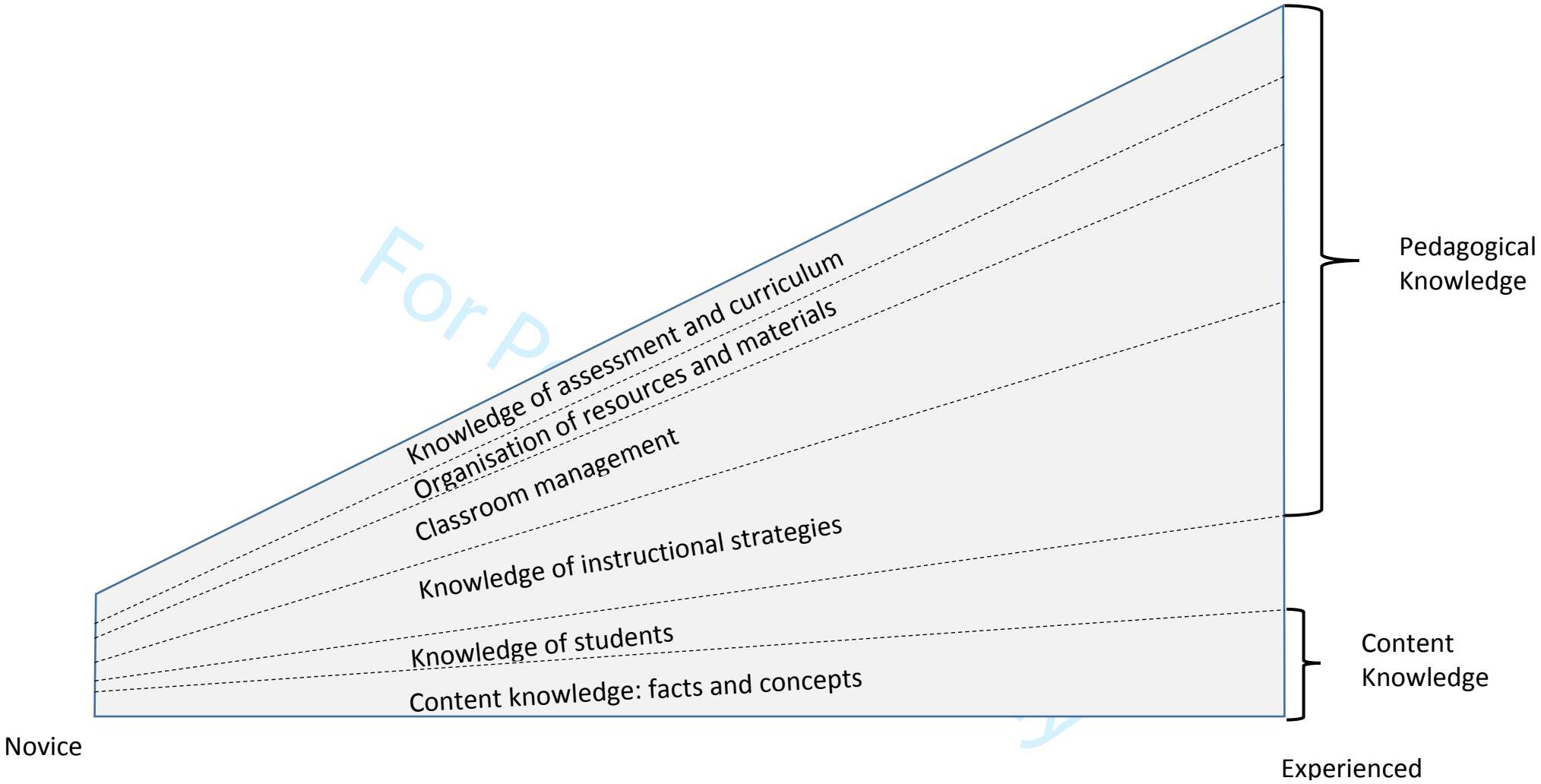

Figure 2: Pedagogical Content Knowledge: A structure for the amalgam